

HALO WHITE DWARFS AND THE HOT INTERGALACTIC MEDIUM

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ABSTRACT

We present a schematic model for the formation of baryonic galactic halos and hot gas in the Local Group and the intergalactic medium. We follow the dynamics, chemical evolution, heat flow and gas flows of a hierarchy of scales, including: protogalactic clouds, galactic halos, and the Local Group itself. Within this hierarchy, the Galaxy is built via mergers of protogalactic fragments. Hot and cold gas components are distinguished, with star formation occurring in cold molecular cloud cores, while stellar winds, supernovae, and mergers convert cold gas into a hot intercloud medium. We find that early bursts of star formation lead to a large population of remnants (mostly white dwarfs), which would reside presently in the halo and contribute to the dark component observed in the microlensing experiments. The hot, metal-rich gas from early starbursts and merging evaporates from the clouds and is eventually incorporated into the intergalactic medium. The model thus suggests that most microlensing objects could be white dwarfs ($m \sim 0.5M_{\odot}$), which comprise a significant fraction of the halo mass. Furthermore, the Local Group could have a component of metal-rich hot gas similar to, although less than, that observed in larger clusters. We discuss the known constraints on such a scenario and show that all local observations can be satisfied with present data in this model. The most stringent constraint comes from the metallicity distribution in the halo. The best-fit model has a halo that is 40% baryonic, with an upper limit of 77%. Our model predicts that the hot intragroup gas has a total luminosity 1.5×10^{40} erg s $^{-1}$, and a temperature of 0.26 keV, just at the margin of detectability. Improved X-ray data could provide a key constraint on any remnant component in the halo.

Subject headings: dark matter — galaxies: evolution — galaxies: interactions — nuclear reactions, nucleosynthesis: abundances cosmology — dark matter, galactic evolution

1. Introduction

Recently there has been renewed interest in the nature of the dark matter in galaxy halos, motivated by the results of microlensing experiments. Observations toward the Magellanic clouds (e.g., Alcock et al. 1995; Aubourg et al. 1993) and toward the Galactic bulge (e.g., Udalski et al. 1993) have detected gravitational microlensing and inferred the presence of dark, massive compact halo objects (MACHOs). Furthermore, a recent binary detection in the direction of the LMC, along with average event durations of about 2.5 months, may imply masses of order $\sim 0.5M_{\odot}$, suggestive of white dwarfs.

At the same time, X-ray observations of clusters (Mushotzky 1993) and groups (e.g., Mulchaey, Davis, Mushotzky, & Burstein 1996, 1993; Pildis, Bregman, & Evrard 1995; Ponman, Bournier, Ebeling, & Böhringer 1996) have discovered a large amount of hot, metal-rich gas. Where it is observed, this gas is a substantial fraction of the baryonic mass—it is the dominant baryonic component of clusters, and is comparable to the galactic component in groups. Indeed, it appears that most baryons in the universe are in the form of this hot X-ray emitting gas.

The relatively high metallicity ($Z \sim 0.3Z_{\odot}$ for clusters, $Z \sim 0.1Z_{\odot}$ for groups) of this gas is impressive and demands that the material has undergone a significant amount of stellar processing during an earlier epoch of star formation. Such an epoch would also produce remnants, mostly white dwarfs. If this epoch is a general consequence of the formation of the bulge and halo of spirals like the Milky Way, as well as the ellipticals of rich clusters, it could account for the observed microlensing objects.

Although white dwarfs are attractive MACHO candidates, there are important constraints on such objects and their formation (Ryu, Olive, & Silk 1990). These include background light from the early evolution, the present luminosity of the halo, and the metal and helium content of the disk and halo stars. While these place important constraints on model parameters, they do not rule out a significant white dwarf halo population, as we shall show.

In modeling these galaxy aggregates and their hot gas components, one must account for the dependence of these systems on the morphology of the constituent galaxies. On the one hand, the hot gas in clusters and groups appears correlated with the luminosity of elliptical and S0 galaxies (Arnaud et al. 1992). This

suggests that the hot gas arises from the violent merging associated with these morphological types. On the other hand, it also seems well established (e.g., Rich 1990) that the morphology of the bulge and halo of spiral galaxies is quite similar to that of ellipticals and S0's. This suggests that the bulge and halo of spirals may have experienced a similar epoch of star formation and outflow during their formation. The difference in the morphologies may relate to the larger angular momentum or shallower gravitational potential of spirals (Zurek et al. 1988), such that some gas survives halo formation, and settles afterwards into spiral arms.

With this background in mind, we find that a likely, and perhaps inevitable, consequence of the formation of the bulge and halo is the formation of a large remnant population in the Galactic halo, along with hot X-ray emitting gas in the Local Group and intergalactic (i.e., extragroup) medium. While our model should be widely applicable, in this paper we concentrate on the Local Group.

Given the detection of dark microlensing objects, as well as the need for significant amounts of dark baryonic matter *somewhere* (Copi, Schramm, & Turner 1995; Fields, Kainulainen, Olive, & Thomas 1996) halo white dwarfs are a very conservative candidate (e.g., Larson 1987; Ryu, Olive, & Silk 1990; Silk 1993). This is particularly so since red and brown dwarfs are apparently excluded as halo candidates (Bahcall, Flynn, Gould, & Kirhakos 1994; Graff & Freese 1996). Here we make a specific though schematic model, and assess the plausibility of the white dwarf hypothesis.¹ As we will see, the model can be made to work but not without some assumptions (e.g., one must alter the halo initial mass function). In any case, the model is eminently testable, and perhaps has already been tested by X-ray observations in other groups. Indeed, should one find this model and the halo white dwarf hypothesis untenable, then it follows that the dark baryons and the MACHOs must take an even more exotic form.

2. Local Group Properties

We take the Local Group to have a mass $\sim (3 - 5) \times 10^{12} M_{\odot}$ (Fich & Tremaine 1991). Its luminous component is dominated by two galaxies, one of which

¹Others have suggested that the microlensing objects might be remnants from an early Population III; see Fujimoto, Sugiyama, Iben, & Hollowell (1995).

(the Galaxy) has a visible mass $\sim 7 \times 10^{10} M_{\odot}$. The total mass of the Galaxy is uncertain and depends on the radius, i.e., $M_{\text{tot}} \sim 5 \times 10^{11} M_{\odot} (R_{\text{halo}}/50 \text{ kpc})$. This implies that the dark halo has a mass within 50 kpc of $\sim 4 \times 10^{11} M_{\odot}$, some or all of which will be in the form of microlensing objects and other dark baryons. We consider models with up to 90% the total mass in nonbaryonic dark matter, at the group scale. The baryonic fraction at the halo scale, however, can be much less.

In many galaxy groups, hot intergalactic gas is found (e.g., Mulchaey et al. 1993, 1996; Pildis, Bregman, & Evrard 1995; Ponman, Bournier, Ebeling, & Böhringer 1996). This gas is a significant and sometimes dominant component of the baryonic mass. The hot gas-to-galaxy mass ratio ranges from 0.3 – 3. The gas also contains metals, with $Z \sim (0.1 - 0.2) Z_{\odot}$. While the ROSAT metallicity determinations are uncertain (Davis, Mulchaey, Mushotzky, & Burstein 1996), recent measurements with ASCA (Fukazawa et al. 1996) suggest that the gas metallicities in groups could have a larger spread than those of clusters. In any case, the metallicity is clearly not primordial, indicating that a significant fraction of material has been processed in stars before they are incorporated into the intragroup medium.

If the gas is in hydrostatic equilibrium with the gravitational potential of the group, then the temperature distribution determines the total mass. Furthermore, the observed temperatures tend to tightly cluster around $T = 1 \text{ keV}$ for most groups observed thus far (Mulchaey et al. 1996). This implies that the *total* masses are similar, with most observed group masses lying in the range $(1.5 - 2.5) \times 10^{13} M_{\odot}$. This is a tighter range than the span of *luminous* mass in galaxies and gas.

However, it is not clear that all optically identified groups evidence hot gas. Several analyses of ROSAT observations have found that the presence of detectable gas is strongly correlated with the morphologies of the constituent galaxies (e.g., Pildis, Bregman, & Evrard 1995). The trend is very similar to that found in galaxy clusters: the hot gas mass is correlated with the presence of early-type (E and S0) galaxies. Indeed, Mulchaey et al. (1996) emphasize that there is at least one bright ($L_B \gtrsim 5 \times 10^{10} L_{\odot}$) elliptical galaxy in *every* group for which hot gas has been detected.

On the other hand, Ponman, Bournier, Ebeling, & Böhringer (1996), also using ROSAT data, have re-

cently claimed the positive detection of hot gas in spiral-dominated Hickson compact groups. They find that the gas in these groups has a lower temperature ($\sim 0.3 \text{ keV}$), and thus, a lower surface brightness than that in groups with early-type galaxies. The discrepancies between these results and those of previous groups attests to the difficulty in trying to measure or put limits on such a relatively dim diffuse component. Ponman et al. (1996) note that differences between their results and others trace to details of the analysis, e.g., subtraction of galactic and background emission. As Davis, Mulchaey, Mushotzky, & Burstein (1996) point out, these are not always straightforward issues. Hence, we regard the issue of hot gas in spiral-dominated galaxies as presently ambiguous.

In the Local Group specifically, there has not been direct observation of hot intergalactic gas. However, Suto et al. (1996) have argued that such a component is allowed within current direct limits. Indeed, they suggest that this is a source of the excess low-energy component in the diffuse X-ray background. Suto et al. (1996) model a gas distribution that could lead to the excess radiation; their distribution implies a total mass in hot intergalactic gas of about $\sim 3.5 \times 10^{11} M_{\odot}$. Of course, the existence of hot gas in spiral-dominated groups is a central premise in this scenario. Pildis & McGaugh (1996) show that the observational limits on such gas (if it is similar to other spiral-rich groups) require any Local Group gas to have too low a mass to provide the soft X-ray background.

3. Hierarchical Collapse Model

Motivated by hierarchical clustering scenarios for structure formation, we compute the evolution of a hierarchy of self-similar mass scales. The three scales are (1) protogalactic clouds, all of which reside in (2) galaxy halos, themselves moving within the (3) group. Within a spiral protogalaxy, the clouds merge to become ultimately the disk and bulge. However, we do not distinguish the disk and bulge. Their formation does not significantly affect the halo or group evolution once the last merging has occurred and the star formation (and gas outflow) in the halo has diminished.

The dynamics of the three components are described (Mathews & Schramm 1993) as the radial evolution $R(t)$ of a spherical overdensity, from its initial expansion (starting at $t = 10^8 \text{ yr}$) through the de-

parture from Hubble flow and collapse to a fixed final radius. The halo collapse is halted at 50 kpc.

For each component in the structure hierarchy, we follow the evolution of matter in the form of gas, stars and remnants, and possibly also non-baryonic dark matter. We also compute the helium and metal evolution, and follow the temperature of the hot gas. Our model is schematic but contains the necessary features for testing and constraining our basic hypotheses. Its structure (summarized pictorially in figure 1) is as follows.

3.1. Level 1: Protogalactic Clouds

In this simple model we assemble galaxies from a distribution of protogalactic fragments within expanding and contracting galactic halos. At the level of the protogalactic clouds, we consider the system to be composed of three components: cold star-forming molecular clouds; heated ejecta from the clouds; and stars and remnants. We assume that non-baryonic dark matter (if there is any) is unimportant at this scale.

Let us first consider the cold star-forming gas and hot gas components. These components are most dramatically affected by star formation and merging. Stars form from the cold gas and return a fraction of their material as hot ejecta. This hot stellar ejecta further mixes with and heats the local cold gas mass into the hot component. In addition, material is heated during mergers (e.g., White et al. 1993) as the relative kinetic energy of the merging clouds is converted into internal energy of the merged system. Also, cooling of the hot gas component returns material back to cold star forming regions.

We write the coupled equations for the evolution of the cold and hot gas components for an average cloud experiencing all of these processes as:

$$\begin{aligned} \dot{m}_{g1}^{\text{cold}} = & -(1 + \mathcal{R}\eta_{\text{mix}})\psi(t) \\ & + \lambda_{\text{merge}}m_{g1}^{\text{cold}} \\ & + \lambda_{\text{cool}}m_{g1}^{\text{hot}} , \end{aligned} \quad (1)$$

$$\begin{aligned} \dot{m}_{g1}^{\text{hot}} = & \mathcal{R}(1 + \eta_{\text{mix}})\psi(t) \\ & + \lambda_{\text{merge}}m_{g1}^{\text{hot}} \\ & - \lambda_{\text{cool}}m_{g1}^{\text{hot}} \\ & + \dot{m}_{\text{in}1} - \dot{m}_{\text{out}1} . \end{aligned} \quad (2)$$

The first term on the right hand side of equations (1) and (2) describes the formation of stars and ejecta.

\mathcal{R} is the usual (e.g., Tinsley 1980) returned fraction of material from stars in the instantaneous recycling approximation. It depends on the initial mass function. The hot ejecta is assumed to sweep up and mix with the cold cloud material; the resulting mixture contributes to the hot gas component. We therefore include an additional factor of η_{mix} describes the number of equal masses of local interstellar material that is heated into the hot component along with the stellar ejecta. The rate of incorporation of cold gas into new stars is $\psi(t)$.

The second term on the right hand side in equations (1) and (2) describes the effects of mergers. Here, λ_{merge} is the merger rate per cloud. On average, during each merger, the cloud mass will double. The third term describes the cooling from hot to cold gas, with the cooling rate per particle given by λ_{cool} . The last terms in Eq. (2) accounts for infall and outflow of gas. The infall term \dot{m}_{in} gives the rate at which hot halo gas is incorporated into the hot gas component of the clouds. The outflow rate $\dot{m}_{\text{out}1}^{\text{hot}}$ we attribute to the evaporation of hot gas. The physics behind each of these terms is discussed in §3.4.

For our purposes, we take the cold star forming gas to be truly cold gas with $T \lesssim 100$ K. The hot gas component is approximated by assuming that all gas at higher temperatures is isothermal and homogeneous within each of the levels of structure.

If we combine equations (1) and (2) we can recover the familiar instantaneous recycling equation for one gas component;

$$\dot{m}_{g1}^{\text{cold}} + \dot{m}_{g1}^{\text{hot}} = -(1 - \mathcal{R})\psi(t) + \dot{m}_{\text{in}}^{\text{eff}} - \dot{m}_{\text{out}} , \quad (3)$$

where the effective infall rate, due to mergers as well as the influx of halo gas, is $\dot{m}_{\text{in}}^{\text{eff}} = (\dot{m}_{g1}^{\text{cold}} + \dot{m}_{g1}^{\text{hot}})\lambda_{\text{merge}} + \dot{m}_{\text{in}1}$. The outflow rate is just $\dot{m}_{\text{out}} = \dot{m}_{\text{out}1}^{\text{hot}}$.

As in MS93 we assume that protogalactic mergers disperse the stars and remnants into the halo. The evolution equation for the mass m_{r1} in stars and remnants remaining in a cloud becomes:

$$\dot{m}_{r1} = (1 - \mathcal{R})\psi(t) + (1 - \kappa)\lambda_{\text{merge}}m_{r1} . \quad (4)$$

Here κ is a measure of the efficiency for the mergers to disperse stars and remnants. Specifically, the average fraction f of stars and remnants born at time t_0 which survive merging up to time t is

$$f = e^{-\kappa \int_{t_0}^t dt' \lambda_{\text{merge}}} \quad (5)$$

We will take $\kappa = 1$.

Since stars return all of their ejecta into the hot component, the metallicity in the cold star forming gas is only indirectly enriched by cooling from the hot component. Thus, from Eq. (1) we write for the evolution of the total mass in metals in the cold star forming gas ($Z_1^{\text{cold}} m_{g1}^{\text{cold}}$):²

$$\begin{aligned} \frac{d(Z_1^{\text{cold}} m_{g1}^{\text{cold}})}{dt} = & Z_1^{\text{hot}} \lambda_{\text{cool}} m_{g1}^{\text{hot}} \\ & - Z_1^{\text{cold}} \left[(1 + \mathcal{R} \eta_{\text{mix}}) \psi(t) \right. \\ & \left. + m_{g1}^{\text{cold}} \lambda_{\text{merge}} \right]. \end{aligned} \quad (6)$$

This reduces to a simple evolution equation for the metallicity of the cold gas,

$$\dot{Z}_1^{\text{cold}} = (Z_1^{\text{hot}} - Z_1^{\text{cold}}) \lambda_{\text{cool}} \frac{m_{g1}^{\text{hot}}}{m_{g1}^{\text{cold}}} . \quad (7)$$

Clearly, the equilibrium metallicity of the cold star-forming component is equal to the hot component metallicity. This equilibrium is, however, only achieved after a time given by the cooling time scale, $\lambda_{\text{cool}}^{-1}$ times the ratio of cold to hot gas masses.

By an analogous process to the derivation of Eq. (7), the evolution of metallicity in the hot gas component can be written

$$\begin{aligned} \dot{Z}_1^{\text{hot}} = & [y_Z + (1 + \eta_{\text{mix}}) \mathcal{R} (Z_1^{\text{cold}} - Z_1^{\text{hot}})] \frac{\psi(t)}{m_{g1}^{\text{hot}}} \\ & + (Z_{g2}^{\text{hot}} - Z_{g1}^{\text{hot}}) \frac{\dot{m}_{\text{in}1}}{m_{g1}^{\text{hot}}} \end{aligned} \quad (8)$$

where y_Z is the mass fraction of newly synthesized material in the ejecta. As usual, y_Z depends on both the initial mass function, and on the stellar nucleosynthesis yields as a function of mass (and metallicity).

By a similar derivation, the temperature of hot gas in the halo is determined from an energy balance equation. This leads to an evolution of internal energy per unit mass ϵ_1 in the hot gas,

$$\begin{aligned} \dot{\epsilon}_1 = & \left[\epsilon_{\text{SN}} - \epsilon_1 (1 + \eta_{\text{mix}}) \right] \frac{\mathcal{R} \psi(t)}{m_{g1}^{\text{hot}}} \\ & + \lambda_{\text{merge}} \epsilon_{\text{merge}} \end{aligned} \quad (9)$$

²We explicitly show only the metal evolution here and below, but from this the expressions for the helium evolution follows trivially.

$$\begin{aligned} & - (\epsilon_1^{\text{out}} - \epsilon_1) \frac{\dot{m}_{\text{out}}^{\text{hot}}}{m_{g1}^{\text{hot}}} \\ & + (\epsilon_2 - \epsilon_1) \frac{\dot{m}_{\text{in}1}}{m_{g1}^{\text{hot}}} \\ & - 2 \frac{\dot{R}_1}{R_1} \epsilon_1 , \end{aligned}$$

where ϵ_{SN} is the average energy per unit mass in all stellar ejecta averaged over an appropriate initial mass function. This term is dominated by supernovae whose energy release is $E_{\text{ej}} \sim 10^{51}$ erg per supernova. Averaging over the initial mass function $\phi(m)$ then gives

$$\epsilon_{\text{SN}} = \frac{\int dm \phi(m) E_{\text{ej}}(m)}{\int dm \phi(m) m_{\text{ej}}} \quad (10)$$

which is independent of the normalization convention of ϕ . For a typical initial mass function, this gives values of order $\epsilon_{\text{SN}} \sim 10^{49}$ erg M_{\odot}^{-1} .

The quantity ϵ_1^{out} is the average energy per unit mass for the material exiting the cloud. For an ideal gas, the temperature is simply related to ϵ_1 by, $T_1 = (2\epsilon_1 \mu / 3k N_A)$, where μ is the mean molecular weight of the gas and N_A is Avagadro's number.

The last term in Eq. (9) accounts for the $p dV$ work done as the cloud expands or contracts; the radial dependence is given by the collapse of a spherical overdensity. The cloud radius R_1 is the average tidal radius

$$R_1 = \left(\frac{m_1}{m_2} \right)^{1/3} R_2 , \quad (11)$$

where m_1 is the total average cloud mass

$$m_1 = m_{g1}^{\text{cold}} + m_{g1}^{\text{hot}} + m_{r1} , \quad (12)$$

and m_2 is the average halo mass defined below (Eq. 13). We assume that the relative momentum of the merger goes into heating the cloud gas. Thus, we have $\epsilon_{\text{merge}} = E_{\text{merge}} / M_{\text{merge}} = v_{\text{rel}}^2 / 2$.

3.2. Level 2: Galactic Halos

For our purposes, galactic halos are treated as a homogeneous assembly of protogalactic clouds and hot gas, possibly having a component of nonbaryonic dark matter. The total mass of the galactic halo is then

$$m_2 = n_c m_1 + m_{g2} + m_{r2} + m_2^{\text{NB}} , \quad (13)$$

where n_c is the number of protogalactic clouds, m_{g2} is the mass of hot gas which has exited the clouds to

reside in the halo, and m_{r2} is the mass of stars and remnants which have been dispersed from clouds into the halo. The mass of the nonbaryonic component, if present, is m_2^{NB} .

The equation describing the evolution of the (hot) gas component in the halo is:

$$\dot{m}_{g2} = n_c (\dot{m}_{\text{out}1} - \dot{m}_{\text{in}1}) - \dot{m}_{\text{out}2} + \dot{m}_{\text{in}2} , \quad (14)$$

where $\dot{m}_{\text{out}2}$ is the rate at which the hot gas is ejected from the halos as described below and $\dot{m}_{\text{in}3}$ is the possible inflow of gas from the intragroup medium.

The rate at which stars and remnants are injected into the halo from mergers can be inferred from Eq. (4),

$$\dot{m}_{r2} = \kappa n_c m_{r1} \lambda_{\text{merge}} . \quad (15)$$

The equation governing the evolution of metallicity in the halos will be

$$\dot{Z}_2 = (Z_1^{\text{hot}} - Z_2) \frac{n_c \dot{m}_{\text{out}1}}{m_{g2}} + (Z_3 - Z_2) \frac{\dot{m}_{\text{in}2}}{m_{g2}} , \quad (16)$$

where n_c is the number of cold protogalactic clouds in the halo. Similarly the internal energy per unit mass, ϵ_2 , of gas in the halo is determined from an energy balance equation:

$$\begin{aligned} \dot{\epsilon}_2 = & (\epsilon_1^{\text{out}} - \epsilon_2) \frac{n_c \dot{m}_{\text{out}1}^{\text{hot}}}{m_{g2}} \\ & - \left(\epsilon_2^{\text{out}} - \epsilon_2 \right) \frac{\dot{m}_{\text{out}2}}{m_{g2}} \\ & + (\epsilon_3 - \epsilon_2) \frac{\dot{m}_{\text{in}2}}{m_{g2}} \\ & - \lambda_{\text{cool}} \epsilon_2 - 2 \frac{\dot{R}_2}{R_2} \epsilon_2 . \end{aligned} \quad (17)$$

The number of clouds decreases exponentially with the number of mergers:

$$\dot{n}_c = -\lambda_{\text{merge}} n_c . \quad (18)$$

3.3. Level 3: Hot Intra-Group Medium

The equations governing the evolution of the intra-group medium are analogous to those for the galactic halos, but at the level of the group nonbaryonic dark

matter may be a dominant contributor. Thus, for the total group mass we write,

$$m_3 = n_h m_2 + m_{g3} + m_3^{\text{NB}} , \quad (19)$$

where n_h is the number of galactic halos in the group, m_{g3} is the mass of the hot X-ray intragroup medium, and m_3^{NB} is the contribution from nonbaryonic dark matter.

The evolution equation for the intragroup medium is then,

$$\dot{m}_{g3} = n_h (\dot{m}_{2\text{out}} - \dot{m}_{\text{in}2}) - \dot{m}_{3\text{out}} , \quad (20)$$

and $\dot{m}_{3\text{out}}$ is the rate at which the gas is lost from the group.

The equation governing the evolution of metallicity in the intragroup medium is then

$$\dot{Z}_3 = (Z_2 - Z_3) \frac{n_h \dot{m}_{2\text{out}}}{m_{g3}} , \quad (21)$$

and the energy balance equation is

$$\begin{aligned} \dot{\epsilon}_3 = & (\epsilon_2^{\text{out}} - \epsilon_3) \frac{n_h \dot{m}_{\text{out}2}}{m_{g3}} \\ & - (\epsilon_3^{\text{out}} - \epsilon_3) \frac{\dot{m}_{\text{out}3}}{m_{g3}} \\ & - \lambda_{\text{cool}} \epsilon_3 - 2 \frac{\dot{R}_3}{R_3} \epsilon_3 , \end{aligned} \quad (22)$$

from which temperature of the intragroup medium can be inferred.

3.4. Cooling, Star Formation, Mergers, and Mass Loss

The evolution is given by equations (1–22). What remains is to specify the various input quantities, i.e., the rates for cooling, star formation, merging, and mass loss.

The metallicity-dependent cooling rate λ_{cool} is derived from the calculations of Böhringer & Hensler (1989). For the temperatures appropriate for the hot gas, the cooling is dominated by brehmsstrahlung emission from electrons. These losses are written in terms of the cooling function Λ , which gives the energy loss rate per unit density. Given the number density at a given scale n_i , one may then compute the energy loss rate per particle: $\dot{E}_i = n_i \Lambda$, and then the cooling rate $\lambda_{\text{cool}} \equiv \dot{E}/E$.

We allow star formation to be induced both by mergers and intrinsic star formation processes within

the clouds (MS93). In MS93 it was shown that intrinsic star formation is more important during the subsequent evolution as material settles into a disk. To describe the merger-induced star formation for all of the merging substructures within a collapsing halo, MS93 proposed a schematic model of colliding virialized protogalactic clouds within an expanding and contracting halo. We adopt that formulation here.

Specifically, we presume that the fragments virialize as they form. The collision rate per cloud within this virialized velocity distribution can be written,

$$\lambda_{\text{merge}} = (n_c - 1)\sigma v/V, \quad (23)$$

where n is the number of protogalactic clouds within a volume V , σ is an average collision cross section, and v is the virial velocity ($v \sim [0.4GM_h/R_h]^{1/2}$), where M_h is the total gravitational mass of a galactic halo, and R_h is the radius of the galactic halos, approximated as a collapsing spherical overdensities. We define halos as those regions which evolve to become independent gravitationally bound ensembles of gas and stars at the present time. All halos themselves are viewed as the result of merging internal structure. Hence we only describe merging within the halos and not merging between halos. This is largely a matter of semantics.

The number of protogalactic clouds decreases exponentially with the integral of the merger rate (Eq. 18),

$$n_c(t) = n_c(0) e^{-\int_0^t \lambda_{\text{merge}} dt'}, \quad (24)$$

where the initial number of clouds, $n_c(0)$, is given by the ratio of the total initial halo baryonic mass to the initial cloud mass. Thus, $n_c(0) \sim 10^6$ for this schematic model. For the merger cross section σ we use $\sigma = \pi R_t^2$, with a tidal radius $R_t = 2R_1$ to include gravitational effects (Binney & Tremaine 1987).

Near the end of the collapse of the halos, the combined effects of conservation of angular momentum and heating will dissipate the radial motion. In our schematic model, we approximate these effects by halting the halo collapse at a size of a typical present dark-matter halo, ($R_2 \sim 50$ kpc). The cloud radii are fixed by Eq. (11), and the group collapse is halted when the radius reaches the present size of the Local Group, $R_3 \sim 700$ kpc.

The merger-induced stellar birth rate thus is taken as proportional to the mass of gas mass participating in mergers per unit time. The intrinsic, quiescent star formation rate is taken as $\propto \rho_{\text{cold}}^n m_{\text{gas}}^{\text{cold}}$, where

$n = 1/2$ in our case. The total star formation rate is the sum of the two terms:

$$\psi(t) = (\alpha_{\text{mrg}} \lambda_{\text{merge}} + \beta_Q \rho_{\text{cold}}^{1/2}) m_{\text{g1}}^{\text{cold}}, \quad (25)$$

Note that we have parameterized the strength of merger-induced star formations in terms of the dimensionless efficiency α_{mrg} . Typical numbers for α_{mrg} are $\sim 1\%$ (MS93). The coefficient of the quiescent piece is taken as $\beta_Q = \beta_q \Lambda_0$, where $\Lambda_0 = 1.7 \times 10^{-4}/(M_\odot \text{ kpc}^{-3})^{-1/2} \text{ Gyr}^{-1}$. Typical values of the dimensionless scaling β_q are 1–5 (MS93).

Finally, we must specify the rate at which hot gas is ejected from, or falls into, the clouds, halos, and the group. We first calculate the outflow due to evaporative mass loss. We assume that the hot gas is distributed homogeneously within an object. The rate of loss of hot gas is then just given by the fraction of a Maxwellian thermal distribution of velocities in excess of the escape velocity at the surface of the structures at all three levels. Thus, we write,

$$\begin{aligned} \dot{m}_{gi}^{\text{hot}} &= 3\zeta_{\text{loss}} \frac{\langle v(> v_e) \rangle}{R_i} m_{gi}^{\text{hot}} \\ &\equiv \lambda_{\text{out}} m_{gi}^{\text{hot}} \end{aligned} \quad (26)$$

Where, i denotes clouds, halos, or the group, and $\zeta_{\text{loss}} \leq 1$ is a dimensionless scale factor depending on the geometry of the cloud; $\zeta_{\text{loss}} = 1$ for a sphere. The factor $\langle v(> v_{\text{esc}}) \rangle$ is the average velocity of all particles above the escape velocity $v_{\text{esc}}^2 = 2GM_i/R_i$:

$$\begin{aligned} \langle v(> v_{\text{esc}}) \rangle &= \frac{\int_{v_{\text{esc}}}^{\infty} dv v^3 f_{MB}(v)}{\int_0^{\infty} dv v^2 f_{MB}(v)} \\ &= \frac{1}{4\sqrt{\pi}} (1 + x_i) e^{-x_i} v_T \end{aligned} \quad (27)$$

where f_{MB} is the Maxwellian distribution. The average thermal velocity is $v_T^2 = 2kT_i/\mu m_p$, and μm_p is the average mass of a gas particle. $x_i = GM_i/R_i kT_i$ is the ratio of gravitational binding energy to thermal energy, and is small typically.

Similarly, the average energy loss per unit ejected mass of material is

$$\begin{aligned} \epsilon_i^{\text{out}} &= \frac{\langle \epsilon v(> v_{\text{esc}}) \rangle}{\langle v(> v_{\text{esc}}) \rangle} \\ &= \frac{1 + x_i + x_i^2/2}{1 + x_i} \frac{2kT_i}{\mu m_p} \end{aligned} \quad (28)$$

which for small x_i gives $\epsilon_i^{\text{out}} \simeq 2kT_i/\mu m_p = 4\epsilon_i/3$.

Using similar derivations, we have computed inflow of halo (group) gas into the clouds (halos). We note that this inflow has two components. First, some material is accreted simply due to the motion of the halo or cloud through the surrounding medium—the finite size of these substructures will lead to the capture gas that falls within their geometric cross section $\sigma = \pi R_i^2$. Second, the hot gas particles surrounding the substructures will accrete due to their random thermal motion. We assume that these particles quickly equilibrate with the ambient gas. Together these two effects lead to an infall term of the form

$$\dot{m}_{\text{ini}}^{\text{hot}} = \frac{4}{3} \zeta_{\text{loss}} \left(\frac{R_i}{R_{i+1}} \right) \frac{m_{\text{gi}+1}^{\text{hot}} (v_{i+1}^T + v_c)}{R_{i+1}}, \quad (29)$$

with $v_c^2 \equiv Gm_{i+1}/R_{i+1}$ the cloud (halo) circular velocity.

3.5. Initial Mass Function and Stellar Yields

The initial mass function (IMF) is important for our scenario in several respects. As we have noted, it affects the parameters of our model, namely the returned fraction \mathcal{R} , yields y_Y and y_Z , and specific energy injection ϵ_{SN} . Moreover, the crucial impact of the IMF for our scenario is that it determines the ratio of low mass stars to high mass stars in the halo. Low mass stars ($m \lesssim 0.9M_\odot$ for halo metallicities) will still be burning today. While these stars are faint, they would be detectable, and heavily favored by an IMF similar to that of present disk stars. As a result, such stars would today outnumber by far the halo remnants, and their net contribution to the halo luminosity would be large (Ryu, Olive, & Silk 1990). Thus, remnants cannot be a significant component of the halo if the halo IMF is similar to that inferred for disk stars. To allow for a significant population of halo white dwarfs, they must have been formed from an IMF which strongly favored the formation of intermediate- to high-mass stars over low-mass stars (Ryu, Olive, & Silk 1990).

Given the different physical conditions during the formation of the halo (e.g., frequent mergers, higher temperatures, lower metallicities), it is at least plausible that the star forming process then was different than that of disk stars. Indeed, there are arguments for an early IMF that is skewed towards higher masses (see Silk 1993; Bond, Arnett, & Carr 1984; Adams & Fatuzzo 1996).

Therefore, we have chosen the simple log-normal IMF parameterization, as suggested by both obser-

vational (Miller & Scalo 1979) and theoretical arguments (Adams & Fatuzzo 1996 and refs therein): $\ln \phi(\ln m) = \ln \phi_0 - [\ln^2(m/m_c)/2\sigma^2]$. We investigate the effect of variations of the centroid mass m_c and the dimensionless width σ . We take the IMF bounds to be $(0.1, 100)M_\odot$, with a black hole cutoff at $18M_\odot$ (Brown & Bethe 1995). In fact, our results for metal yields are insensitive to these limits. With these parameters, we obtain a returned fraction $\mathcal{R} = 0.375$.

The stellar yields are taken from Maeder (1992). We follow both helium and metallicity Z . These abundances are particularly powerful constraints when used together. The helium yields are mainly from intermediate mass stars ($m \lesssim 8M_\odot$), while the metal yields come primarily from high mass stars. Thus, the IMF must strike a balance between the two mass ranges to avoid an inappropriate ratio of helium to metals. With our IMF, we find $y_Y = 0.0139$ and $y_Z = 0.0354$.

4. Results

In this hierarchical merging picture we take the clouds to be the initial building blocks of all structure. Thus, while we assume the clouds to be comprised initially of hot and cold gas, we assume baryons in the halos and the Group to be initially within clouds only. Thus, by definition the initial gas in the halos and group is zero. The initial metallicity is zero, while we take a primordial helium abundance of $Y = 0.235$.

We have run the model for plausible ranges of the input parameters. The two models we present here are: (1) a “best-fit” model which has appropriate final masses and metallicities, while also optimally satisfying other constraints (§§4.4–4.6); and (2) a “maximum remnant” model which has the highest possible halo remnant mass without violating the constraints. Parameters of these models are summarized in Table 1. Unless otherwise noted, numerical results will be given for the best-fit model.

For all models, the qualitative results are as follows. There is generally a high initial merger rate, which lasts for $\lesssim 1$ Gyr. This reduces the number of protogalactic clouds from 10^6 to about 100 while producing a burst of star (and hot gas) formation. The star formation rate and cloud number evolution appear in Figure 2. Some of the stars are ejected into the halo by the mergers, and on a longer timescale, a wind is ejected—first from clouds, then from halo, and ultimately from the Group. When the halo col-

lapses, after 5 Gyr (Mathews & Schramm 1993), there is an additional burst of merging and star formation. The remaining clouds coalesce into what will eventually become the galactic bulge and spiral arms. With the collapse there is also heating and a reinvigorated wind. Subsequently, all remaining (hot, metal-rich) halo gas is ejected into the intergalactic medium. The evolution of halo and group masses is given in Figure 3.

4.1. Disk and Bulge Formation

The clouds begin with the Jeans mass at recombination, $10^6 M_\odot$. They merge to form the proto-disk+bulge, with a mass $8.1 \times 10^{10} M_\odot$. It is encouraging that, at the end of the halo collapse, most material in the proto-disk is in cold gas which will form disk stars. The evolution of metallicities is given in Figure 4. As seen in the figure, the metallicities grow rapidly in the initial burst, then remain fairly constant until the halo collapse at 5 Gyr. Then the metals rise again as the halo collapses and the disk and bulge are formed. Hence, the halo evolution provides an initial metallicity for the gas of the protodisk. This corresponds to an “initial enrichment” of the disk material, and so avoids overproduction of metal poor disk stars (i.e., the disk G-dwarf problem).

4.2. Halo Formation

In the best-fit model, portrayed in Fig. 3a, the galaxy (=clouds+halo) begins with a mass of $1.35 \times 10^{12} M_\odot$, of which $1.1 \times 10^{12} M_\odot$ is baryonic (all in the clouds). Even higher fractions are allowed, as discussed below (§5). The final galaxy mass is $5.0 \times 10^{11} M_\odot$, of which $2.5 \times 10^{11} M_\odot$ is baryonic; thus 50% of the total Galactic mass is in baryons. Some of these baryons constitute the disk+bulge, as described above. The baryonic mass of the halo remnants alone (excluding the disk+bulge) is $1.7 \times 10^{11} M_\odot$, and the halo nonbaryonic mass accounts for $2.5 \times 10^{11} M_\odot$. Hence, 40% of the dark halo is in remnants, consistent with the microlensing observations.

When combined with mass loss from the other galaxy in the Local Group, there is a total loss of $1.7 \times 10^{12} M_\odot$ of gas from both halos into the intragroup medium. The galactic wind is thus very efficient, as it must be to remove the ejecta that accompanies the remnant production. The remnants themselves are mostly white dwarfs, with 12% neutron stars.

4.3. Group Evolution

In the best-fit model, the Local Group begins (Fig. 3b) with a mass of $5.6 \times 10^{12} M_\odot$, and a baryonic mass of $2.2 \times 10^{12} M_\odot$. At the end of the simulation the group has a total mass $4.3 \times 10^{12} M_\odot$, 17% of which is baryonic. Of the baryonic group mass, $2.9 \times 10^{11} M_\odot$ resides in hot gas. The intragroup gas temperature is 0.26 keV, just at the limit of ROSAT sensitivity. The group as a whole loses $1.4 \times 10^{12} M_\odot$ of gas to the intergalactic medium; thus about 64% of the initial baryonic mass in the group is ejected later into intergalactic space.

It is remarkable that the remnants in the halos, turn out to represent a small fraction of the initial baryonic matter. The galactic winds required to remove the stellar ejecta co-produced with the white dwarfs prove strong enough to remove most gas from the group itself. This amount of hot (ionized) material is consistent with Gunn-Peterson limits on the intergalactic medium *if it does not cool further* (§5.1).

Thus, in the best-fit model we find the dark halo to be 40% microlensing objects. These take the form of stellar remnants, 88% of which are white dwarfs, and the rest neutron stars (and perhaps black holes). In this model the copious production of hot intragroup and intergalactic gas is a natural consequence of white dwarf-dominated halos. We produce a present mass of intragroup gas of $2.9 \times 10^{11} M_\odot$. This corresponds to about 37% of the baryonic mass of the Local Group. This mass is encouragingly near the value ($3.5 \times 10^{11} M_\odot$) implied by the Suto et al. (1996) model for the excess diffuse X-ray background (§2). (But recall the observational controversy §2.)

The X-ray luminosity of the halo is $1.5 \times 10^{40} \text{ erg s}^{-1}$. Let us assume for simplicity that the earth is at the center of this emission, and that the gas extends homogeneously to the edge of the Local group ($R_3 = 700$ kpc in this model). This leads to a total diffuse background of about $4 \times 10^{-2} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$. This is, at its peak energy, about 3 orders of magnitude below the observed diffuse soft X-ray background. We therefore find the diffuse Local Group radiation to be negligible. The contribution is thus much lower than that suggested by Suto et al. (1996), who postulate a similar (but larger) intragroup gas mass, but posit a temperature of 1 keV as opposed to 0.26 keV in this model.

4.4. Mass budget

The most basic constraint on our model is the requirement that it reproduce the observed mass and metal budget of the Local Group. The final masses determine the initial masses, but the metallicity values constrain how to get these. Consider the total metal mass production in our model. The total initial baryonic mass is 2.2×10^{12} . Of this, the mass processed into stars and remnants is $M_{rem} = 4.95 \times 10^{11} M_{\odot}$. The total mass into ejecta is just $\mathcal{R}/(1 - \mathcal{R})/M_{rem} = 3.0 \times 10^{11} M_{\odot}$. The total metal mass produced is $y_Z M_{ej} = 1.1 \times 10^{10} M_{\odot}$, and the total new helium mass is $y_Y M_{ej} = 2.8 \times 10^{10} M_{\odot}$.

Now, the average *new* metals from a given star represents a high fraction of that star's ejecta: $y_Z = 0.014 \sim 2/3 Z_{\odot}$. However, this metal-rich ejecta is diluted in several ways. First, it is mixed with η times its mass as it leaves the cold star-forming regions. Then it is mixed into the hot cloud gas, which quickly evaporates into the halo and on to the intra-group medium. Much gas is even evaporated from the Local Group itself, becoming part of an intergalactic (extragroup) medium. Thus, the final mean metallicity must be averaged over all of the baryons (including the ejecta from the Local Groups). One finds that the global average mass fraction is just $0.0049 \simeq 0.25 Z_{\odot}$, an acceptably small value.

The key point here is that star formation does not occur in all regions containing gas (as is often assumed in simple chemical evolution models) but only cold molecular cloud cores. Consequently, the stars represent a small fraction of the total baryonic mass. Furthermore, whereas the stars remain in the galaxies, the gas is dispersed at all levels. The halo can thus contain many remnants but not a large amount of metals.

4.5. Nucleosynthesis

Nucleosynthesis provides an important additional constraint on this scenario (Ryu, Olive, & Silk 1990; Charlot & Silk 1995; Hegyi & Olive 1986). The burst of star formation which produces the white dwarfs must not overproduce metals and helium. As noted above, the metallicities at the different scales are reasonable. Furthermore, we may test not only the average metallicities, but also the halo metallicity distribution. Figure 5 compares our calculated halo stellar metallicity distribution with the observed globular cluster distribution. The agreement is good for

the most metal-poor ($[Z] < -1$), and thus the oldest, portion of the population.

The halo metallicity distribution strongly constrains the total halo remnant mass in our model. The position of the peak constrains the net star formation rate amplitude. If the star formation rate is too large, the peak is shifted too high. Thus, the need to reproduce the peak at $[Z] \sim -1.5$ limits the mass processed into stars, and so leaves fewer stars available for the halo. From the χ^2 of a fit to the halo metallicity distribution we estimate a 2σ upper limit of a 77% remnant contribution to the halo. Consequently, it seems likely that the halo contains at least some non-baryonic dark matter. In addition, the shape of the distribution is largely sensitive to the relative star formation rate, and to the degree of mixing between the stellar ejecta with the cold gas.

The IMF shape is of course important in determining the metallicities. However, contrary to Ryu, Olive, & Silk, we find no significant constraint on the IMF upper limit, essentially because the ejection of gas removes some of the metals produced by high-mass stars. This is even more so if there is a cutoff for black hole formation as low as $18 M_{\odot}$ (Bethe & Brown 1995). This is

4.6. Halo Luminosity

Several sources of luminosity also provide important constraints.

(1) Low mass stars in the halo are long lived and can lead to an unacceptably high halo mass-to-light ratio (Ryu, Olive & Silk 1990; Richstone, Gould, Guhathakurta, & Flynn 1992); however, in our model, the mass to light ratio is comfortably above these authors limit $M/L_B > 500$ for $R_{halo} = 50$ kpc. We determine the luminosity contributed by all stars still burning in the halo by integration of stellar luminosities, the past star formation rate, and initial mass function, without the instantaneous recycling approximation. We find a mass to total luminosity ratio of $M/L_{tot} = 760$, $M/L_V = 1300$, and $M/L_B = 3500$.

(2) Light from the bursts of star formation can lead to a large diffuse background (Charlot & Silk 1995; Zepf & Silk 1996). Using a population synthesis model we have preliminarily computed this background assuming the starlight to be unscattered after its emission. These will be discussed in Mathews et al. (1996), but results are consistent with observed constraints. We exceed the Charlot & Silk (1995) limit

of a 10% remnant halo because most of the elements are formed at very large redshift ($z \sim 10$).

(3) The halo white dwarfs will contribute to the white dwarf luminosity function (e.g., Adams & Laughlin 1996; Chabrier, Segretain, & Méra 1996). There is a new constraint from Flynn, Gould, & Bahcall (1996), which requires halo white dwarfs to have an luminosity $M_V \gtrsim 18.4$, for $V - I > 1.8$.

The white dwarf luminosity function in our model is given in Figure 6. The two peaks corresponding to the two bursts of star formation. The strongest constraint comes from the more recent peak produced at the epoch of halo collapse. These white dwarfs have cooled to present luminosities of $\sim 10^{-5.5} L_\odot$. This would correspond to a bolometric magnitude of 18.4. However, the bolometric correction (Liebert, Dahn, & Monet 1988), would probably reduce the visible luminosity to $M_V > 20$, well below the Flynn, Gould, & Bahcall limit (similar to the findings of Kawaler 1996). The low luminosity of the white dwarfs derives in part from their very old age, but also because the population comes from a shifted IMF. Since the progenitors are more massive stars, they died sooner and so the remnants have had longer to cool. Indeed, our adopted IMF centroid of $2.3M_\odot$ is that of Adams & Laughlin (1996), who chose it specifically to obey the luminosity function constraints in the disk.

4.7. Parameter Sensitivity

Our results depend sensitively on several of the model parameters. Parameter values for our best-fit model are summarized in column 3 of Table 1. Among the most important parameters are those that determine the shape of the IMF. We find a good fit for a centroid (c.f. §3.5) $m_c = 2.3M_\odot$, and a width $\sigma = 1$. Note that this centroid is that of Adams & McLaughlin (1996). However, they advocated a tighter width to avoid metallicity problems which we do not require in our model because metals are efficiently ejected in the hot wind. Indeed, the width we use is essentially the present value (Miller & Scalo 1979).

Other IMF parameters are allowed, but to obey the observational constraints, these must be near the ones we have adopted. As discussed above (§3.5), the centroid must be $\gtrsim 1M_\odot$ to avoid significant production of long lived, low mass stars still burning in the halo. However, the centroid must not be too high to avoid untenably large metal yields. The width must also be not so large that it allows too many low mass stars,

but not so narrow that metal yields are too small and helium yields too large. Thus, the need for a dark halo, and for a reasonable nucleosynthesis, drive the IMF parameters to the range of those we have chosen.

The other important parameters involve star formation and ejecta. The star formation parameters (eq. 25 and Table 1) are reasonable and consistent with previous results (MS93), derived from requiring consistency among various comochronometers. The quiescent term dominates, controlling the mass budget, but the merger term is also important. The ratio of the merger to quiescent contribution controls the position of the peak in the halo metallicity distribution (Fig. 5).

For the ejecta, the most important parameter is the degree of mixing η_{mix} . A higher value leads to more dilution of the ejecta, which leads to lower metallicity and temperature in the hot gas. The observed lower temperatures and metallicity of the hot gas in groups demands that $\eta_{\text{mix}} > 1$.

5. The Remnant Contribution to the Dark Halo Mass

Given that (1) there is good evidence for dark matter in the Galactic halo, and that (2) microlensing objects are the first positively detected dark matter in the halo, a key question arises: how much of the dark halo is in MACHOs? In this context it is important to note that our best model does not give an all-remnant halo. Such a model is attractive for its simplicity, but we find that our best fit prefers only $\sim 40\%$ of the dark halo mass in remnants, with the balance in non-baryonic material. The strongest constraint on the white dwarf halo fraction is the halo metallicity distribution. Increasing the white dwarf fraction requires increasing the star formation rate; this leads to halo metallicities whose distribution peaks too high (§4.7). The “maximum remnant” model is that having the 2σ upper limit for the halo fraction (as set by the halo globular cluster metallicity distribution). Its parameters are summarized in Table 1; in it the halo remnant mass fraction is 77%. This upper limit can be raised somewhat if we increase the stellar merger dispersal efficiency κ (see §3.2). While it is difficult to increase the halo remnant fraction, it is easy to decrease it. If the winds are less efficient (e.g., if $\zeta_{\text{loss}} < 1$), then more material is recycled in the clouds. Thus a lower star formation amplitude is required and fewer stars are available to eject at early

Table 1: Model Parameters Adopted

Model Feature	Parameter	Best-Fit	Max Remnant
IMF	m_c	$2.3 M_\odot$	same
	σ	1.6	same
Star Formation	α_{mrg}	0.007	0.002
	β_q	1	2.5
Ejecta	η_{mix}	8	8
	ζ_{loss}	1	1

times. We find a minimum halo remnant fraction, for $\zeta_{\text{loss}} \lesssim 0.08$, of $\sim 1\%$.

Our findings are to be compared to recent analysis of the MACHO data (Alcock et al. 1996). The microlensing results are still very model-dependent, but it is provocative that they find a best fit for $\sim 50\%$ of the halo being made up of $0.5^{+0.3}_{-0.2} M_\odot$ objects. The question of whether one can put stronger constraints on the MACHO halo fraction in our model leads to the issues raised in the next section.

5.1. X-ray Groups: a Key Constraint

As indicated in §2, there is currently large uncertainty regarding X-ray observations of spiral dominated groups. However, while the observations are ambiguous, what seems more clear is that spiral-rich groups do not contain hot gas with $T \sim 1$ keV. That is, these systems do not evidence the same kind of diffuse emission as groups with early-type galaxies. If hot gas exists in these groups, it must have either low mass ($\lesssim (1-3) \times 10^{10} M_\odot$), or a low temperature, near or below the ROSAT threshold $T_{\text{th}} \lesssim 0.3$ keV. Indeed, Mulchaey, Mushotzky, Burstein, & Davis (1996) suggest that these systems do have cool ($T \lesssim 0.3$ keV) gas, and argue that this may have been detected as high-ionization quasar absorption lines. Furthermore, given the morphological similarity of the bulge and halo with early-type galaxies, it would be surprising if *no* hot gas were found in these systems.

At any rate, the observations seem to rule out that the gas is both massive and hot in spiral-rich groups. However, in our model the temperature and the gas mass are related, as follows.

After the processing of one stellar generation, the ejecta to remnant ratio is $\mathcal{R}/(1 - \mathcal{R})$. Mixing with unprocessed cold material gives a total hot gas to remnant ratio $(1 + \eta_{\text{mix}})\mathcal{R}/(1 - \mathcal{R})$. In our model, $\mathcal{R} = 0.38$, so $M_{\text{gas}} > M_{\text{rem}}$ for $\eta_{\text{mix}} > 1.7$ (which holds in our case). This already means that the mass

of ejected gas must be larger than the halo baryon mass (assuming that most hot gas escapes). Consequently, if the limits on gas in spiral-dominated groups apply—i.e., if the gas were to have $T \gtrsim 0.3$ keV—then the mass in halo white dwarfs must be less than the X-ray limits on the gas mass, $\sim 10^{10} M_\odot$. This would be only a small component of the halo.

To allow for a significant gas mass, therefore, one must demand that it avoid the ROSAT limits because it is cool: $T \lesssim 0.3$ keV. However, the gas temperature is related to the gas-to-remnant ratio, as we now show. The total energy in the ejecta is $\mathcal{R}\epsilon_{\text{SN}}M_{\text{rem}}$. This implies that the energy per unit mass of ejected gas is $\epsilon_{\text{gas}} = \mathcal{R}\epsilon_{\text{SN}}M_{\text{rem}}/M_{\text{gas}} = \epsilon_{\text{SN}}(1 - \mathcal{R})/(1 + \eta_{\text{mix}})$. Finally, using the scaling $T_{\text{SN}} = (2/3) \mu m_p \epsilon_{\text{SN}} = 2$ keV, we have $T_{\text{gas}} = 2 \text{ keV}(1 - \mathcal{R})/(1 + \eta_{\text{mix}})$. That is, the gas temperature diminishes with η_{mix} . But we already have seen that having a significant fraction of the halo in remnants, we need the concomitant halo gas to be cool. Using the Ponman et al. (1996) value $T_{\text{gas}} \simeq 0.3$ keV, and with $\mathcal{R} = 0.39$, one finds $\eta_{\text{mix}} \simeq 3$. In our detailed model which includes reprocessing, we find a larger value, $\eta = 8$. Thus, cooler gas results if $\eta_{\text{mix}} > 1$, but only if the bulk of the baryons are in the gas.

5.2. Cosmological Baryon Fraction

In the preceding section we see that our best-fit model finds that a large fraction of baryons, initially in the group, are ejected as an intergalactic medium. This can be reconciled with the total cosmological baryonic budget, as follows. In our scenario, the cosmic baryonic inventory is $\Omega_B = \Omega_{\text{disk+bulge}} + \Omega_{\text{halo}}^{\text{rem}} + \Omega_{\text{LG}}^{\text{gas}} + \Omega_{\text{IGM}}^{\text{gas}} \simeq \Omega_{\text{halo}}^{\text{rem}} + \Omega_{\text{LG}}^{\text{gas}} + \Omega_{\text{IGM}}^{\text{gas}}$ (writing the universal density in component i in units of the critical density: $\Omega_i \equiv \rho_i/\rho_{\text{crit}}$, where $\rho_{\text{crit}} = 3H_0^2/8\pi G$). If most baryons reside in the intragroup and intergalactic diffuse gas, we therefore require $\Omega_{\text{LG}}^{\text{gas}} + \Omega_{\text{IGM}}^{\text{gas}} \simeq \Omega_B \gg \Omega_{\text{halo}}^{\text{rem}}$.

Observationally, galactic rotation curves imply that galaxy halos have $\Omega_{\text{halo}} \sim 0.02h(R_{\text{halo}}/50 \text{ kpc})$, where R_{halo} is the (unknown) radius of the dark halo (e.g., Peebles 1993). On the other hand, primordial nucleosynthesis calculations give $\Omega_B = (0.015 \pm 0.005)h^{-2}$ (Copi, Schramm, & Turner 1995; Fields et al. 1996). Taking the ratio, we have $\Omega_{\text{halo}}/\Omega_B \sim 1.3h^3$. Consequently, for $h \lesssim 0.9$, $\Omega_{\text{halo}} < \Omega_B$; that is, for reasonable values of h , some baryons are likely to be non-galactic. Indeed, for a low Hubble constant ($h = 0.5$), the *bulk* of the baryons are nongalactic. Furthermore, these relations assume that the halos are entirely baryonic (*not* the case in our best model). Any non-baryonic component in galaxy halos only strengthens the argument.

Thus, we see that the X-ray observations of groups can provide strong constraints on remnants in the halo. Of course, this assumes that the Local Group is like other poor groups. If so, and if the X-ray data is reliable, then these data may provide a key constraint. As we have noted, if there is only a small X-ray gas mass in the Local Group, then there can be few remnants in the halo. Taking the more optimistic view, if the Ponman et al. (1996) result is correct, then there could be a large amount of (as yet unobserved) hot gas in the Local Group, as required in our model.

6. Conclusions

We have shown that, without violating constraints posed by luminosity and nucleosynthesis considerations, one may construct a plausible model in which the dark halo of the Galaxy contains a significant fraction of white dwarfs. These may have already been detected in halo microlensing events towards the LMC, and might also be detected via their luminosity function. The same bursts of star formation which produced the white dwarfs also led to hot, metal-rich intergalactic gas, some of which may still reside in the Local Group. This hot gas could be detectable via its X-rays, and by distortions in the cosmic microwave background radiation (Suto et al. 1996).

Thus, the predictions of the model are testable. If the halo is comprised of white dwarfs then there must be a background of hot, X-ray emitting gas in the Local Group. Conversely, if there is metal-rich hot gas in the Local Group, then a significant fraction of the halo mass must be in remnants. Clearly, further searches for both of these are warranted.

Furthermore, if our galaxy formation scheme is in-

deed universal, then hot gas production and ejection should be a ubiquitous aspect of halo formation. Consequently, X-ray observations of other systems could provide a key constraint on our model. In particular, our model can be directly tested by observations which can unambiguously confirm or deny the presence of hot gas in other spiral-dominated groups. Also, if white dwarfs are ubiquitous in galactic halos, then they may lead to detectable infrared profiles in edge-on galaxies, which may already have been observed (Barnaby & Thronson 1994; Sackett, Morrison, Harding, & Boroson 1994; Lequeux, Fort, Dantel-Fort, Cuillandre, & Mellier 1996; Lehnert & Heckman 1996). Finally, even if our scenario turns out not to be applicable to spiral-dominated groups, it remains that ellipticals must eject gas in strong winds. Thus, our model may still be valid for clusters, which are elliptical-dominated. This will be explored in a subsequent work.

We note as well that in our scenario, just as there is typically a large outflow from the halo, there is also a strong evaporative wind that ejects material from the Local Group. As a result, most baryons eventually reside in hot, intergalactic (as opposed to intragroup) gas. If this gas stays hot, it could perhaps be the ionized intergalactic (as suggested by Gunn-Peterson limits on the neutral intergalactic medium). If it does cool, it presents serious problems, as it would lead to prodigious but unobserved absorption of extragalactic radiation.

Finally, we reiterate that stellar remnants and their associated hot ejecta are conservative candidates for both the halo microlensing objects and for the baryonic dark matter. If these can be ruled out, then we are forced to conclude that the microlensing objects and the dark baryons are something stranger still.

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FIGURE CAPTIONS

1. Schematic diagram of model features.
2. The total galactic star formation rate $\psi = n_c \psi_{cloud}$ (solid curve) and number of clouds n_c (dashed curve) as a function of time. Two bursts of star formation are evident, one shortly after decoupling when the density is high, and one during halo collapse (5 Gyr).
3. Mass evolution for (a) the halo, (b) the local Group.
4. Metallicity evolution for the halo and Local Group.
5. Halo metallicity distribution. The points are for globular clusters (Pagel 1988); only the low metallicity members ($[Z] < -1$) are included in the analysis. The theory (histogram) is binned in the same way as the data, and normalized to minimize χ^2 .
6. The halo white dwarf luminosity function, with L in units of L_\odot . Only results for halo white dwarfs are shown. The two peaks correspond to the two bursts of star formation; the more luminous peak is the more recent burst at $t = 5$ Gyr. This second peak has $M_V \gtrsim 20$, well below current observational limits.













